Computationally efficient predictive muscle-driven simulations of 3D walking

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Introduction

Predictive simulations of walking have a high potential to improve our understanding of walking control. A common approach is to formulate predictive simulations as optimal control problems. Yet, these problems are computationally expensive and hard to solve due to the stiffness and nonlinearity of the musculoskeletal dynamics. These difficulties limit the abilities of researchers to perform predictive simulations using complex musculoskeletal models in a reasonable time. In this study, we address these difficulties by combining computationally efficient numerical methods including direct collocation and automatic differentiation when performing predictive muscle-driven simulations of 3D walking. Additionally, we exploit this computational efficiency to examine different objective functions.

Methods

We used a musculoskeletal model, based on OpenSim's gait2354 model, consisting of 12 segments, 19 degrees of freedom, 54 muscles, and a Hunt-Crossley foot-ground contact model. We formulated the predictive walking simulations as optimal control problems using an implicit formulation of the musculoskeletal dynamics [1]. The problem consisted of finding the states and controls that minimize a weighted sum of muscle activation, total angular momentum [2], and passive joint moments. We simulated a half-gait cycle, imposing right-left symmetry at an imposed walking speed of 1.2 m/s. Initial states and final time were optimization variables. We solved the problem via direct collocation, on a mesh grid of 50 intervals, using IPOPT to solve the resulting nonlinear programming problem. We used custom versions of OpenSim 4.0 and OpenSim's physics engine Simbody [3] that provide derivatives via automatic differentiation through ADOL-C [4]. We relied on the optimization framework CasADi [5] to provide a sparse Jacobian to IPOPT by efficiently querying derivatives from ADOL-C. Finally, we studied the effect of the weights in the objective function on the match between simulated and experimental kinematics and contact forces.

Results and Discussion

The problems converged in 49 minutes on average on a single core, which is substantially faster than results from literature [6]. Simulated joint kinematics were qualitatively similar to experimental data, except that the model produced limited knee flexion during swing (Figure 1). Contact forces exceeded experimental data at heel strike and toe off but had the expected pattern. Objective function weights affected the results, underlining the need for better motor control models. Future work will consist in exploiting this computationally efficient framework to find a walking control model that yields a better match with experimental data.

References

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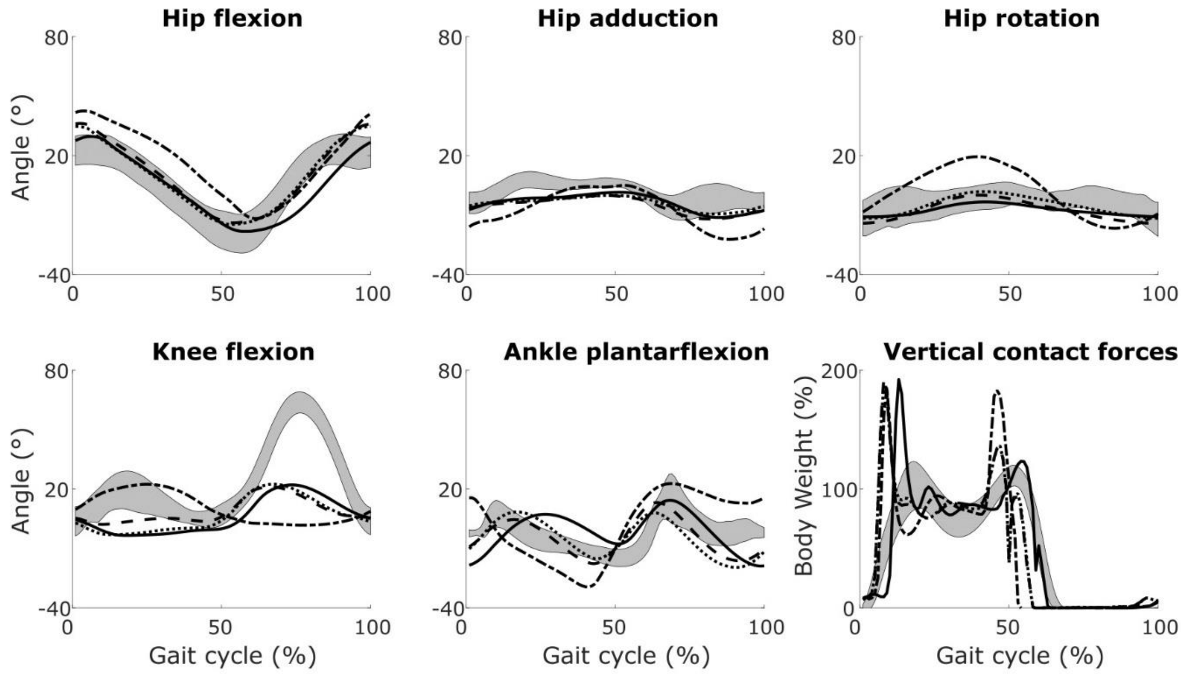

Figure 1. Comparison between experimental (shaded area: mean +/- two standard deviations) and simulated (solid (same weights on all terms), dashed (larger weight on passive moments), dotted (larger weight on angular momentum), dash-dot (larger weight on muscle activation)) kinematics and vertical contact forces.